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AREA SPEED FLOW RELATIONSHIPS : THE EFFECT OF VARYING SIGNAL CAPACITY

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Preface

This paper is one of a series of ITS working papers and technical notes describing the methodology and results of the EPSRC funded project "The definition of capacity in urban road networks : The role of area speed flow relationships". The objectives of the project were to investigate the interaction between vehicle-hours and vehicle-km within a network as the demand for travel increases; to develop improved area speed flow relationships; to use the relationships to explain the process by which networks reach capacity; and to assess the significance for the evaluation of road pricing policies.

The approach used was to collect the vehicle-hours and the vehicle-km directly from a simulation model and thus create relationships between supply and demand in terms of veh-hours/hr and veh-km/hr demanded and also between times per trip and trips demanded.

During the project two models were used. The first was a micro-simulation model called NEMIS. This model was used on hypothetical networks ranging from single link to a six by six grid and finally a ring-radial network. The networks were used to study the effects of changes in OD pattern and the effects of varying capacity on the resulting speed flow measures.

The second model used was SATURN. This model was used to study the same ring-radial as before and a full SATURN model of Cambridge. The SATURN results were then taken one step further in that they were used to create an aggregate model of each network using SATURN in buffer only mode. The related papers discuss issues such as network aggregation. Note that the methodology and terminology was developed as the study progressed and that in particular the method varies between application of the two distinct models.

The reader is directed to the attached appendix A for a full list of publications arising from this project.

1. Introduction

To gain an understanding of the effects of varying signal capacity (signal settings) on the resulting speed flow measures it is best to start with a simple two-armed intersection. The two-armed intersection consists of two entry links each 2.5km in length with a single lane on each arm. The flow on each arm is equal and straight ahead into free-flowing exit links (omitted from the analysis). The signal cycle consists of two stages (one per arm) with inter-greens. The total lost time per cycle is 10 seconds and will remain constant throughout the following tests.

The base signal plan is a cycle of 50 seconds made up of equal greens of 20 seconds (equal flows) and a lost time of 10 seconds. There are two basic ways of changing the cycle time and hence the capacity for some or part of the network :-

A. Maintain Equal Splits

This was done for cycles of 50,70,90,110 and a reduction from the base to 30 seconds. The full settings used including the proportion of the cycle time λ which is green are given in table A.

Cycle	green 1	green 2	λ_1	λ_2
30	10	10	0.33	0.33
50*	20	20	0.40	0.40
70	30	30	0.43	0.43
90	40	40	0.44	0.44
110	50	50	0.45	0.45

* Base plan

Table A. Signal settings with equal splits.

B. Favouring One Link / Direction

The same signal cycles were used i.e. 50,70,90,110 and a reduction from base to 30 seconds but this time link 1 was favoured over link 2. The full settings used are given in table B.

Cycle	Green 1	Green 2	λ_1	λ_2
30	15	5	0.50	0.17
50*	20	20	0.40	0.40
70	40	20	0.57	0.29
90	60	20	0.67	0.22
110	80	20	0.73	0.18

* Base plan

Table B. Signal settings favouring link 1.

Note that the base case c=50 is the same for both type A and type B signal settings and that the flows on each arm are equal for all simulations as the demand is increased.

2. Results

The results are shown in terms of speed, average time/km and actual flow versus demanded flow for link 1, link 2 and the total network. The two types of signal settings are displayed side by side to aid comparison.

Figures 1-6: Speed vs Demanded Flow

For the equal splits (type A) settings the graphs for link 1, 2 and total are very similar. From figure 1,3 or 5 it can be seen that the lower cycle times give a higher speed in free-flow conditions but the situation is reversed as congestion builds up; the lower the flow the lower the optimum cycle time. This is as expected, as the flow increases then the supply/demand ratio $q/\lambda s$ approaches unity or over-saturation first for the shorter cycle times. The 30 second cycle becomes over-saturated at a much lower demand level than the base plan as the change in proportion of green time is relatively greater from 0.4 down to 0.33 compared to the other increases in cycle times with λ values of 0.43, 0.44 and 0.45. For high demands the results tend to converge as the long queues form and dominate the speed measure for the links.

The type B settings favouring link 1 give completely different results. Figure 2 compares with figure 1 for link 1; the base cycle of 50 seconds is the same in each figure. Favouring link 1 as the cycle time is increased increases the free flow speed and more importantly increases the capacity of link 1. This is shown by the spread of the curves and congestion setting in at higher levels of demand. Note that the reduction in cycle time to 30 seconds improves link 1 as the value of λ_1 has actually increased from 0.4 to 0.5 so that this cycle acts between the 50 and 70 second cycles for link 1.

However the benefits for link 1 as the cycle is increased are mirrored by the disbenefits for link 2 as shown in figure 4. Favouring link 1 has the effect of decreasing the λ_2 values compared to the 50 second cycle. In fact the effect can be seen for the first demand level with a marked drop in free flow speeds as the cycle is increased; the 30 second cycle gives similar results to the 110 second cycle as the λ_2 values are similar. However the free flow speed for c=30 at the lowest demand level is higher as this cycle can cope with such a low demand and given this fact it will give a lower delay than the 110 second cycle. The results depend upon the combination of cycle time and λ values. Congestion occurs at lower levels of demand as the λ_2 value is decreased implying a loss of capacity for link 2.

It can be seen from figure 6 that the total network speed suffers as a result of increasing the cycle times whilst favouring one particular link. This is expected as in this case the demanded flows are equal. Figure 5 shows that the total network benefits from increasing the cycle time with equal splits as the demand level is increased beyond the free flow regime.

Figures 7-12 : Av.Time/km vs Demanded Flow

These figures show the inverse of the speed measures. Figures 7,9 and 11 for equal splits are similar and indicate lower times for higher cycles beyond the free flow regime. Figure 8 shows the benefits of increasing λ_1 for link 1 while figure 10 shows the disbenefits for link 2.

Figure 12 for the total network shows that for this case favouring one link as the cycle is increased gives higher travel times/km initially but that as demand increases there comes a cross over point and higher cycles give a benefit over the base case. In fact the last two points for c=110 are very similar to the corresponding points for figure 11 with equal splits. This is because the total green time at the junction is the same for type A and type B settings but the demand must be very high on link 1 for all the green time to be used at saturation flow so that the same number of vehicles pass through the junction per cycle giving similar average travel times/km. The distribution of the travel times/km is different over link 1 and link 2 for type A and B settings.

Figures 13-18 : Actual Flow vs Demanded Flow

With equal splits figures 13,15 and 17 show that higher cycle times increase the actual flow at high demand levels; the total flow increases by about 500 veh-km/hr for the whole junction between c=50 and c=110 for the highest demand level.

Figures 14,16 and 18 show that favouring link 1 increases the flow for link 1 from 2500 to 4000 veh-km/hr from c=50 to c=110 but decreases the flow for link 2 from 2500 to 1000 veh-km/hr between c=50 and c=110. The total flow for the junction is lower than the equal splits case for all levels of demand. The spread of results for cycle times being greatest for total demands of 4000-7000 veh-km/hr where the lower flows are a result of over-saturation on link 2 and wasted green time on link 1. Again there is a cross over point as the demand on link 1 becomes high enough to utilise all the green time.

Note that the 30 second cycle reduces the capacity of the junction for both types of signal settings as the proportion of lost time per cycle has increased dramatically.

3. Conclusions for the two-armed intersection

These results are particular to this junction and this set of demanded flow on each link i.e. equal demanded flows.

Two types of signal setting policy were applied whilst changing the cycle time of the junction. These types have been defined as type A giving equal splits and type B where one direction is favoured over another.

It was shown that for type A settings shorter cycle times are better for free-flow conditions whilst increased cycle times give added benefits for the total network as the flow increases.

For type B settings the favoured direction benefits from increased λ values across all demand levels whilst the other direction disbenefits. The total network suffers until such a point that the saturation flow can be maintained for the favoured direction. This has the effect of introducing inequitable delays in this particular case.

Statements about increasing cycle times increasing capacity must be qualified by stating where the increases in capacity are expected and whether the network as a whole should benefit. The changes in signal settings or capacity seem to have the potential to produce far greater changes in speed flow curves than do changes in OD pattern.

4. The Dewsbury Road Network

The Dewsbury Road network has been simulated for the EU project PRIMAVERA. It is an arterial network consisting of 10 signalised intersections. The network was simulated for ten levels of demand using three different fixed signal plans for the morning peak hour. The signal plans are base 1 the existing signals on the real network based on cycles of 78 and 90 seconds, base 2 modified to give a common cycle time of 88 seconds and a TRANSYT plan based on a common cycle of 120 seconds. Base 2 and the Transyt 120 plan were designed to favour the inbound link flows.

Figures 19-21 show the speed versus demanded flow results for the inbound links, outbound links and the rest of the network respectively. The inbound and outbound links are examples of a type B signal plan i.e. these links are favoured as the cycle time is increased. The transyt 120 plan increases speed for all levels of demand for these directions and the figures are comparable to figure 2. The rest of the network suffers at low demand levels as the cycle time is increased from the base plan i.e. reducing the proportion of green time to the side roads. The transyt 120 plan does however provide benefits to the whole of the network as demand is increased. This is because unlike the 2 armed intersection case, here the link performance is dependent on other links so that benefits to the main arterial can also benefit the side roads (i.e. there is less disruption or blocking-back).

The Dewsbury Road network signal settings have been applied as type B settings i.e. favouring a set of links or directions as the cycle was increased.

5. 6x6 Grid Network

Figure 22 shows the speed versus demanded flow curves for a set of signal cycles for matrix B inbound on the 6x6 grid network. The cycles range from 70 seconds to 130 seconds and the green times were equal for each stage at each junction i.e. type A settings.

At low demand levels the higher cycle times give lower speeds which compares well with figures 1,3 and 5. However the differences between the speeds for the cycles is greater and is thought to be due to the network dimension. Note that the free flow speeds for a single link are between 50-60 km/h whereas the speeds for the grid network drop to between 25-35 km/h, probably due to co-ordination effects i.e. the probability of being delayed in a network of junctions is greater than for one junction with similar signal settings in operation.

For higher levels of demand the results are similar for all the cycle times implying that for this network once congestion has set in blocking-back or disruption within the network is the same irrespective of the cycle times chosen. This maybe a network specific result as gridlock conditions set in and external queues dominate the speed results.

6. Conclusions

Varying signal settings can produce significant shifts in the speed flow measures for signalised networks. The amount and direction of shift depends upon the way in which the signals are designed, here two types of change in cycle time were discussed. The shift will also depend upon the demand level and the network topology. Positive shifts for one area of a network can be mirrored by negative shifts in another area of the network.

The greatest impact on the speed flow curves by varying signal settings is in the area of most interest i.e. where the speed drops off dramatically as demand is increased. Signals can be used to increase or decrease capacity in this region. However note that the effects are also significant at lower demand levels and sometimes the effect is the opposite of that for the higher demand levels.

In general statements about increasing capacity of the network by varying signal settings must be accompanied by a qualifying statement stating whether certain areas or routes are to be favoured; i.e. the signals must be set intelligently.

Further simulations of 2 or 4 junctions with simple flows could be simulated to aid the understanding of the effects of the added network dimension.

7. Comparison to Webster's Delay Formula

Figures 23-26 show the speed versus demanded flow for the 2 armed intersection and the 6x6 grid network based on Webster's delay formula :-

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{c}{q^2}\right)^{1/3} x^{2+5\lambda}$$

where

d	is vehicle delay in seconds
c	is cycle time
λ	is proportion of green time
x	is demand/capacity $q/\lambda s$
q	is vehicle flow (vehicles/sec)
s	is saturation flow (vehicles/sec)

The curves were transformed to give speed against veh-km/hr for the two networks by taking account of the link lengths and making assumptions about the free flow speed and saturation flow in NEMIS. These assumptions were 18 m/s and 2000 vehicles per hour per lane and obviously affect the calibration of the Webster curves to NEMIS.

The figures 23-25 were produced by changing the cycle times and λ values in Webster's formula for the same range of flows. Figure 23-25 should be compared directly with figures 1,2 and 4 respectively. Note that the general shape of the curves and the order of the curves is the same. The Webster curves drop to zero speed for all x greater than 1.0 or over-saturated whereas the NEMIS curves tend towards zero speed as the queues build up. This is because Webster's curve are steady-state compared to the NEMIS curves which are for the two middle slices of the peak hour.

There is also a similar spread of curves for the favoured link 1 and the unfavoured link 2 figures. The capacity in the Webster curves corresponds well with the first major drop in speed for the NEMIS curves for all cycles. The free flow speeds are very slightly higher than in NEMIS but this could be a calibration error. The order of the curves in free flow conditions is the same for the favouring type B settings and for the equal splits. The 30 second cycle gives higher speeds than the 110 second cycle with similar λ values at low flows in both NEMIS and Webster.

Figure 26 should be compared to figure 22 for the 6x6 grid. The curves are very similar indeed until saturation has occurred. The Webster curves were generated for a single intersection with similar properties and then factored up to represent the whole grid network.

On the whole the NEMIS curves follow the Webster predicted curves well up until saturation where the difference is due to the nature of the models. Webster's formula would over-estimate delay caused by a one hour period of over-saturation.

Fig 1

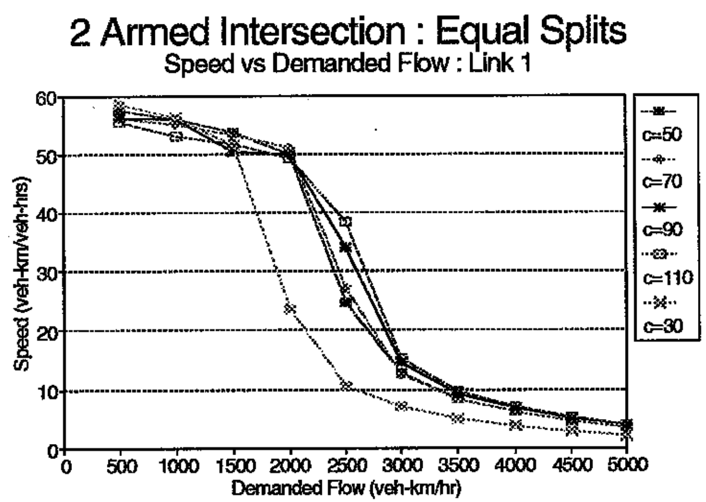


Fig 2

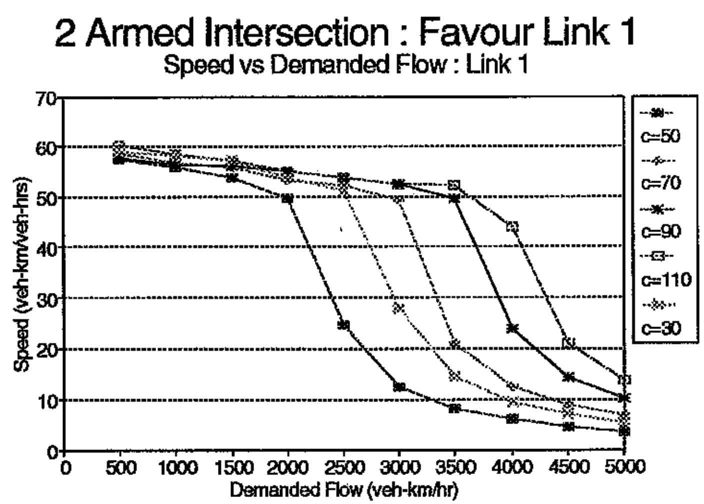


Fig 3

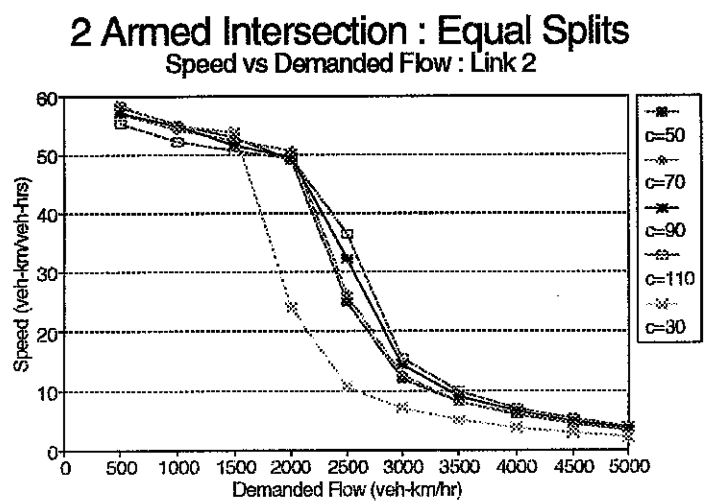
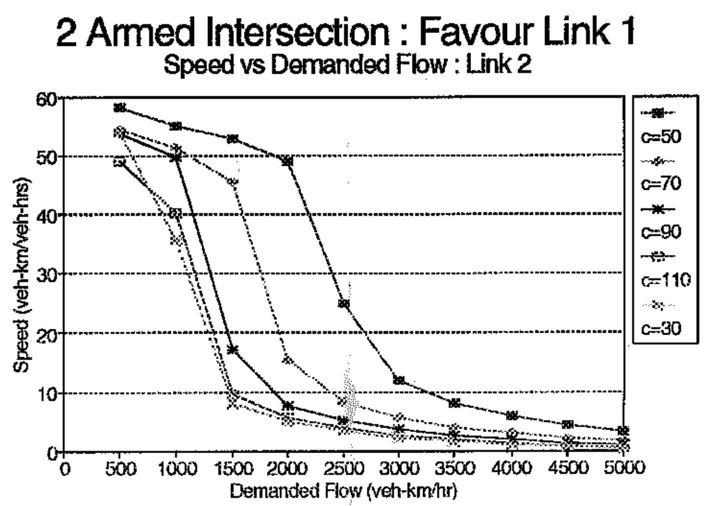


Fig 4



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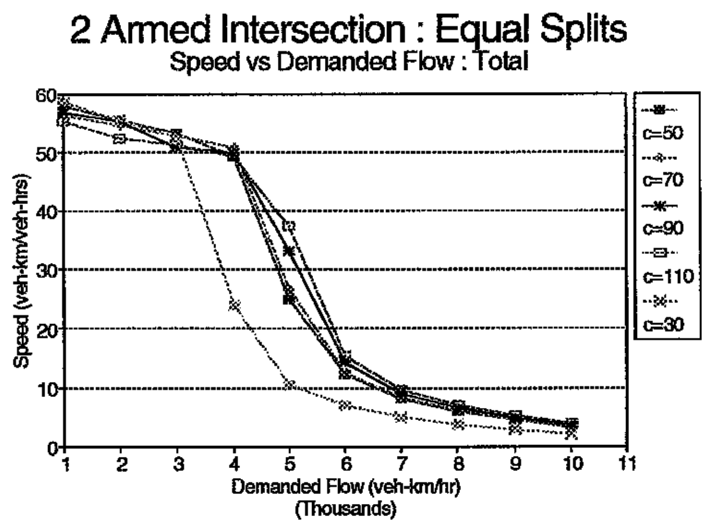

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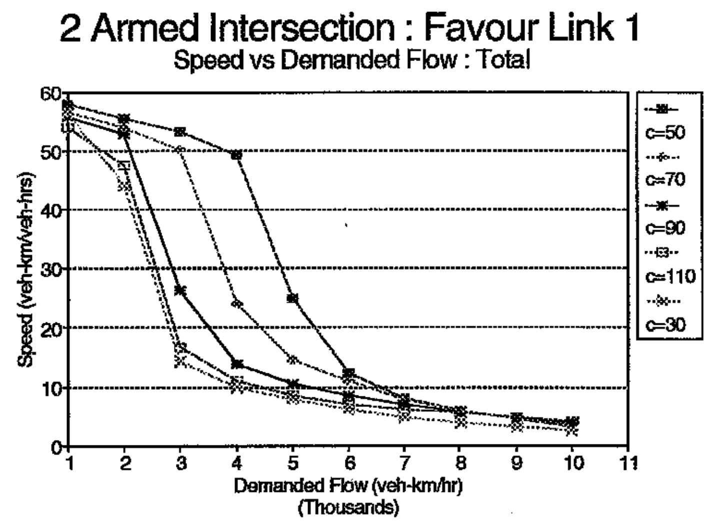

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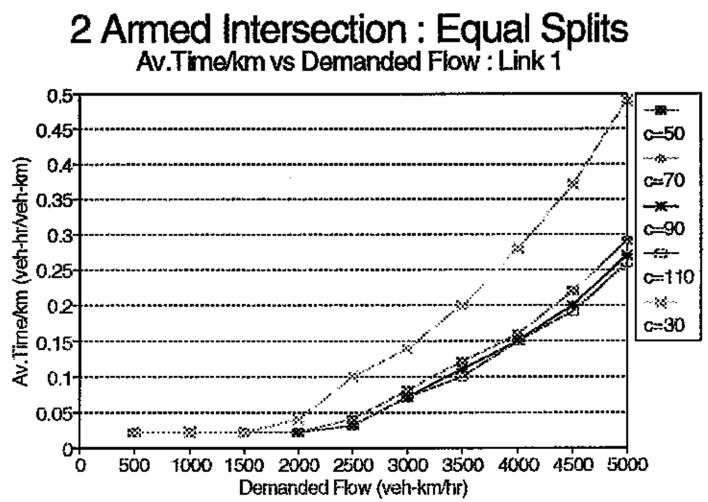

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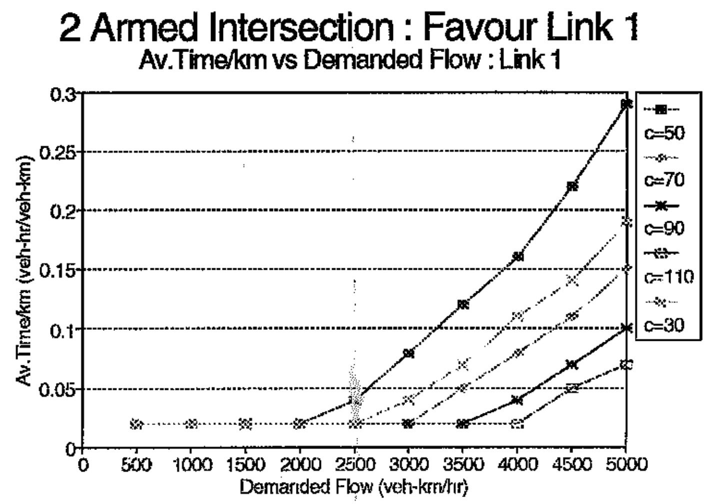

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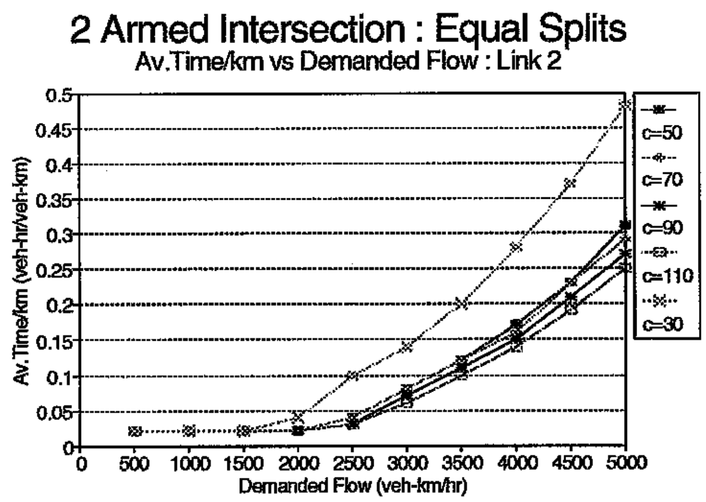
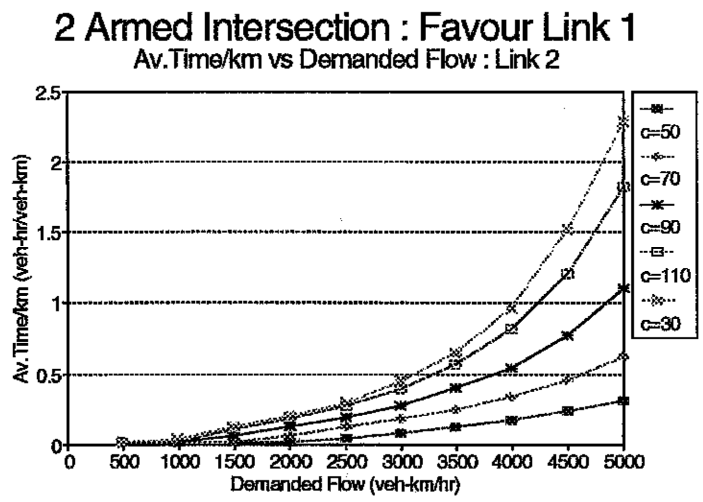


Fig 10



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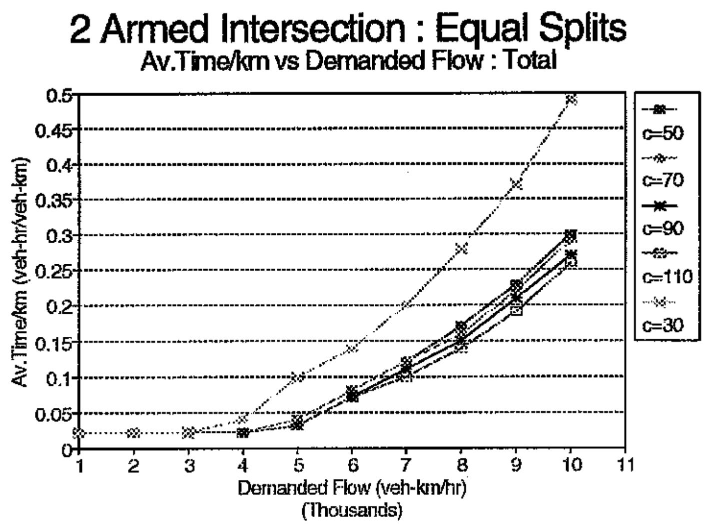
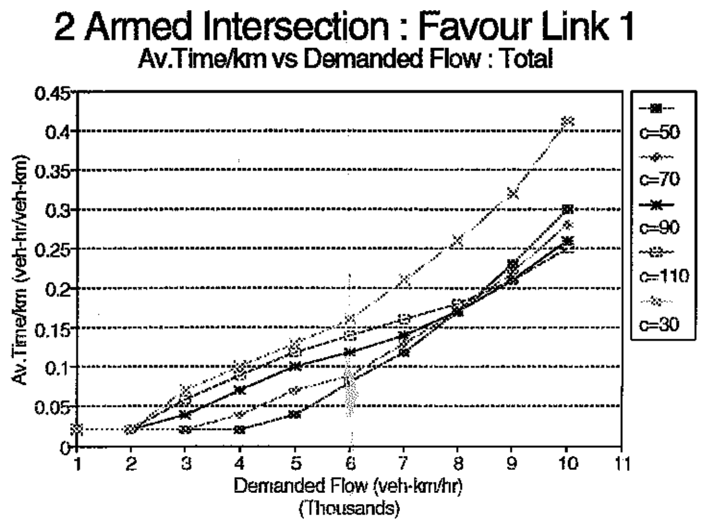


Fig 12



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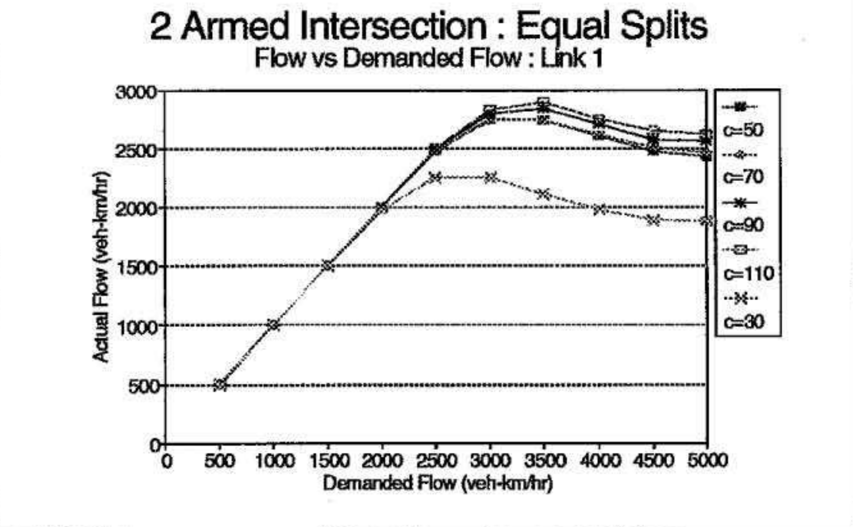

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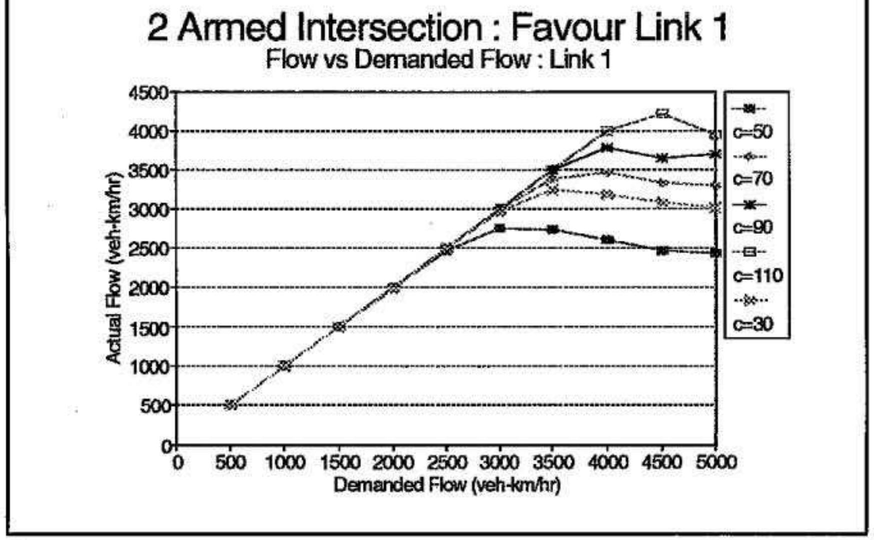

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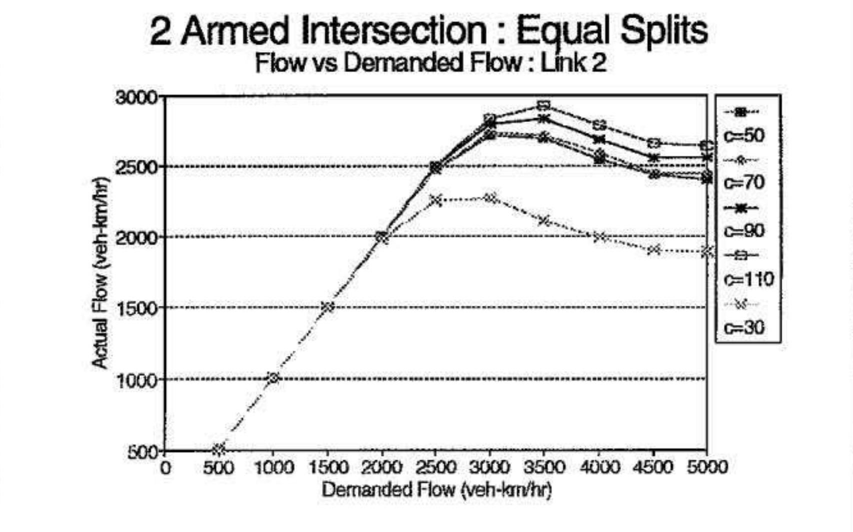

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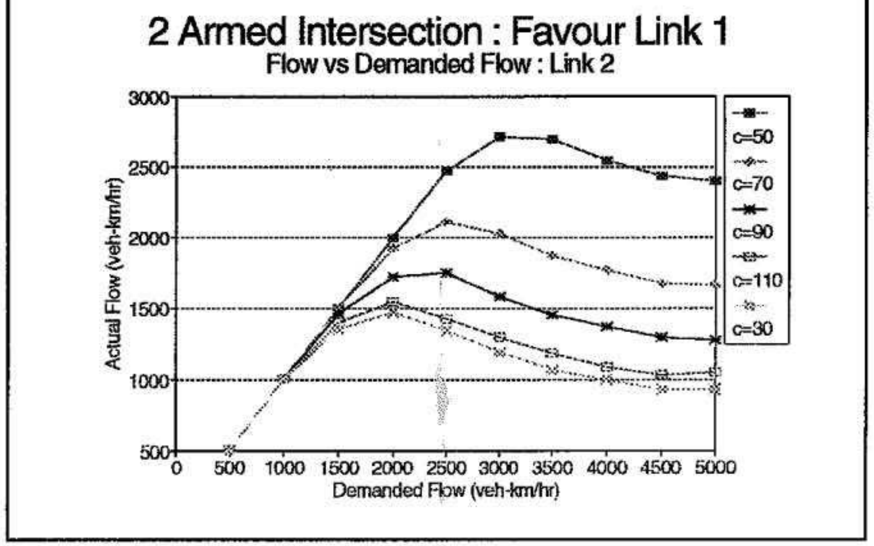

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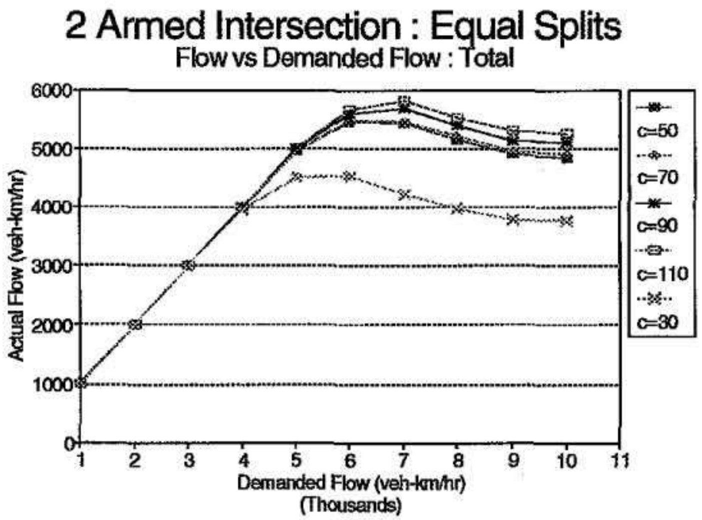

2 Armed Intersection : Equal Splits
Flow vs Demanded Flow : Total
Actual Flow (veh-km/hr)
Demanded Flow (veh-km/hr)
(Thousands)
c=50
c=70
c=90
c=110
c=30

Fig 18

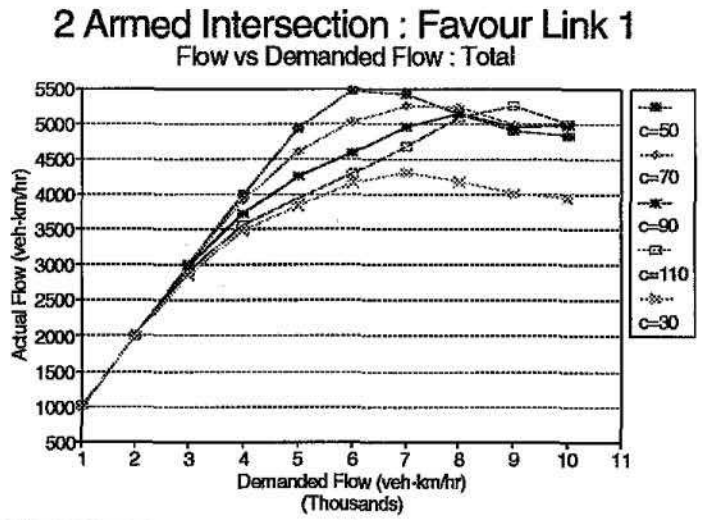

2 Armed Intersection : Favour Link 1
Flow vs Demanded Flow : Total
Actual Flow (veh-km/hr)
Demanded Flow (veh-km/hr)
(Thousands)
c=50
c=70
c=90
c=110
c=30

Fig 19

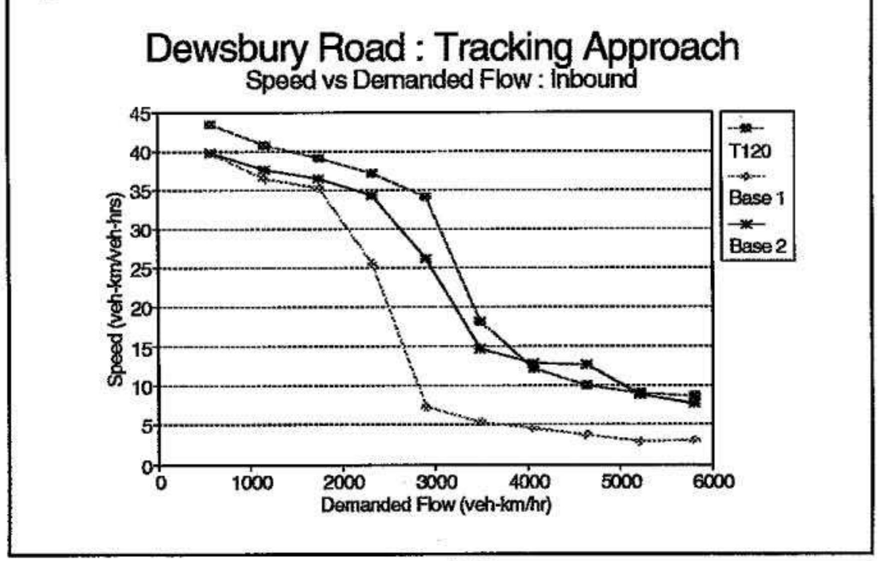


Fig 20

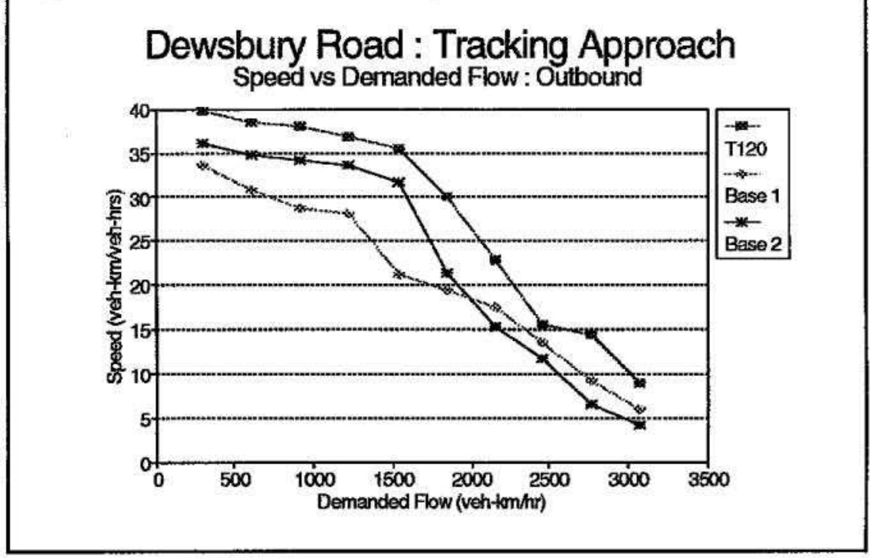


Fig 21

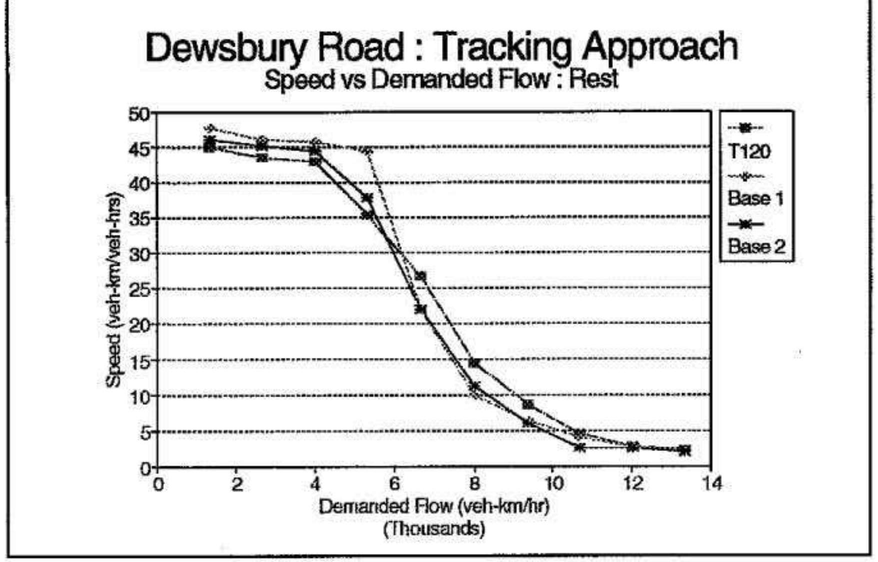
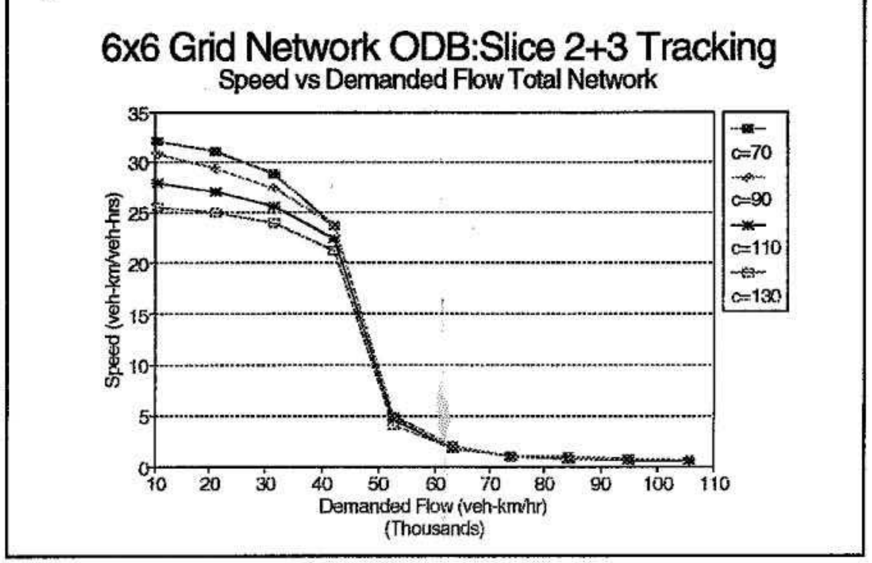


Fig 22



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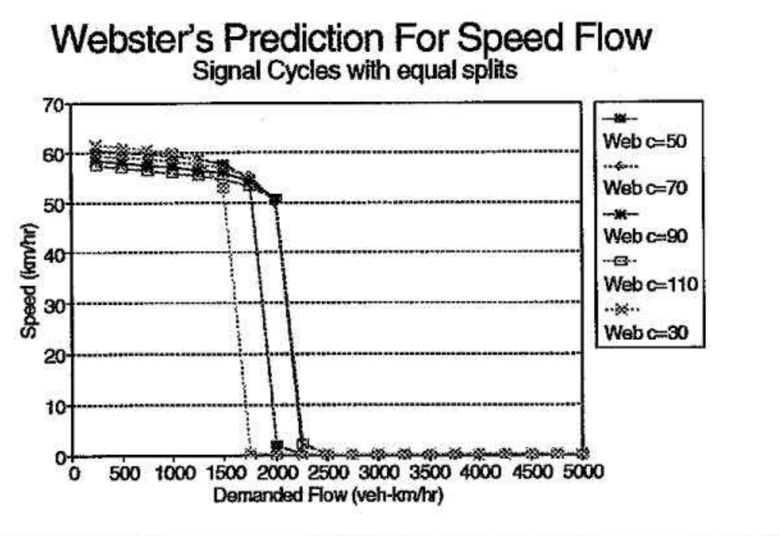

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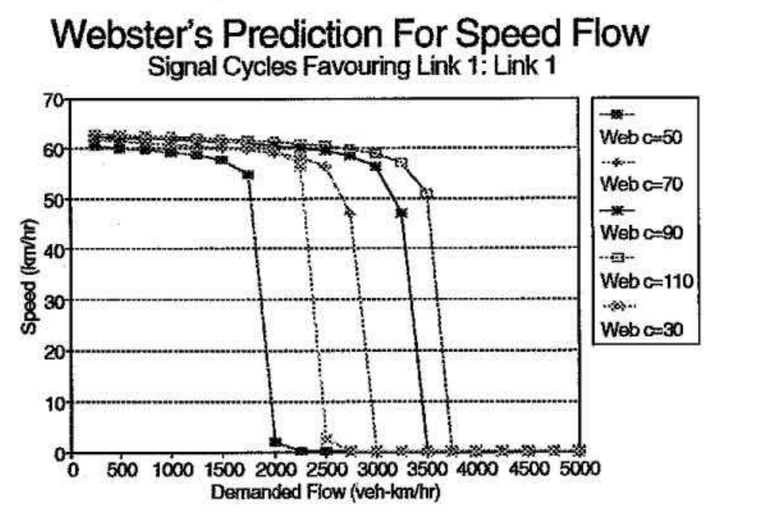


Fig 25

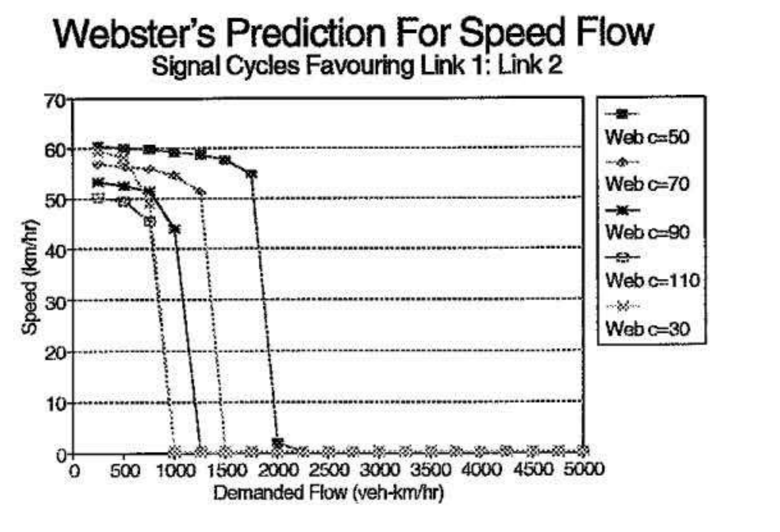


Fig 26

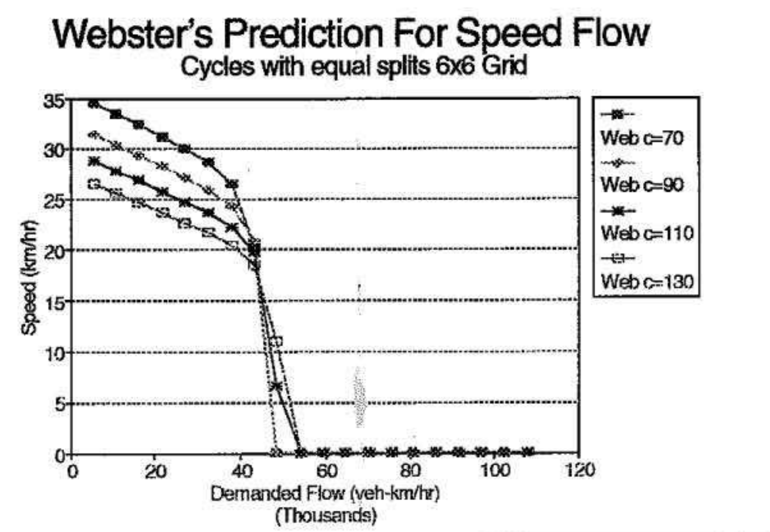
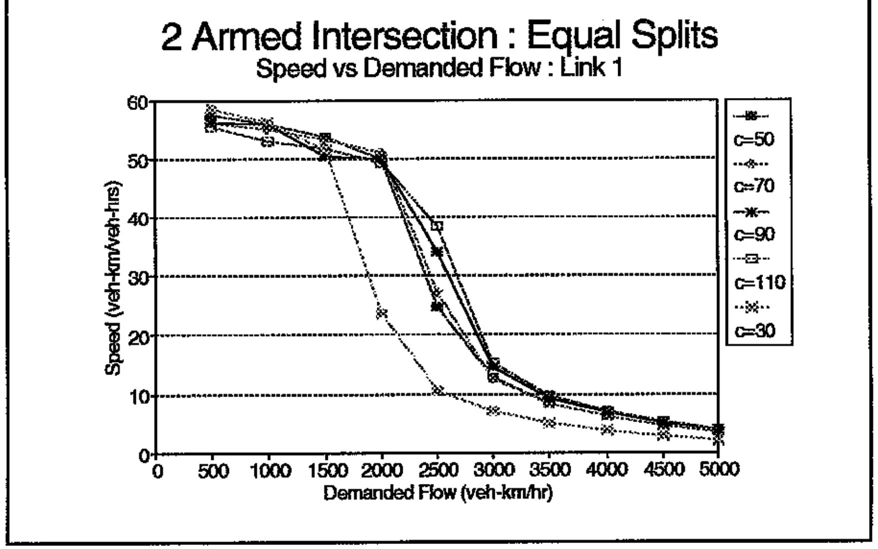


Fig 1



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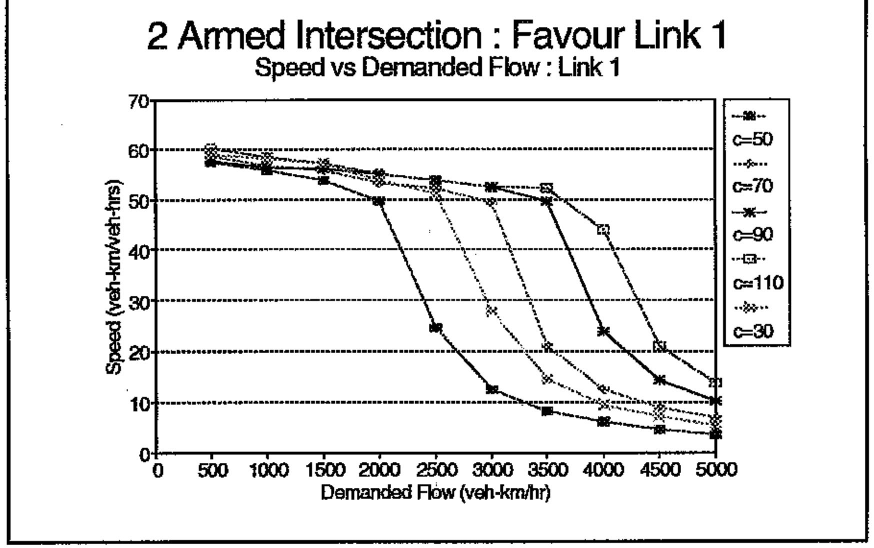

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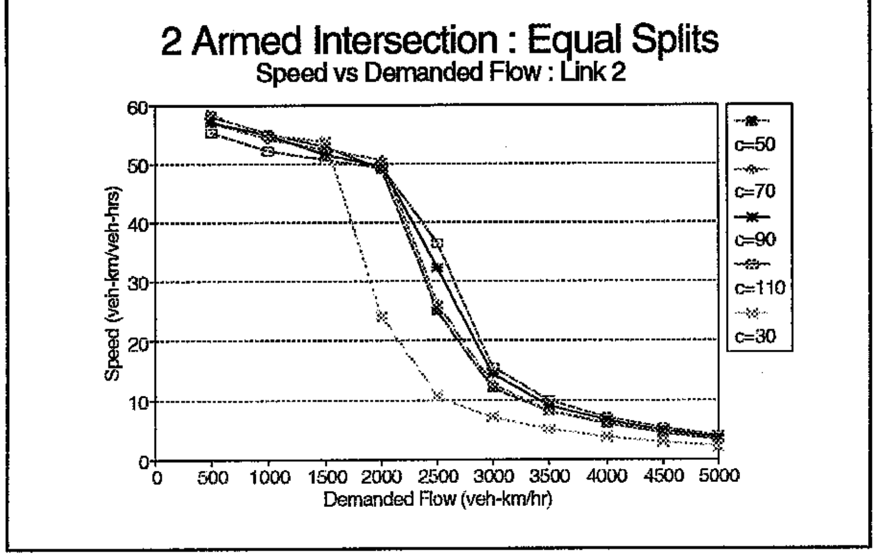


Fig 4

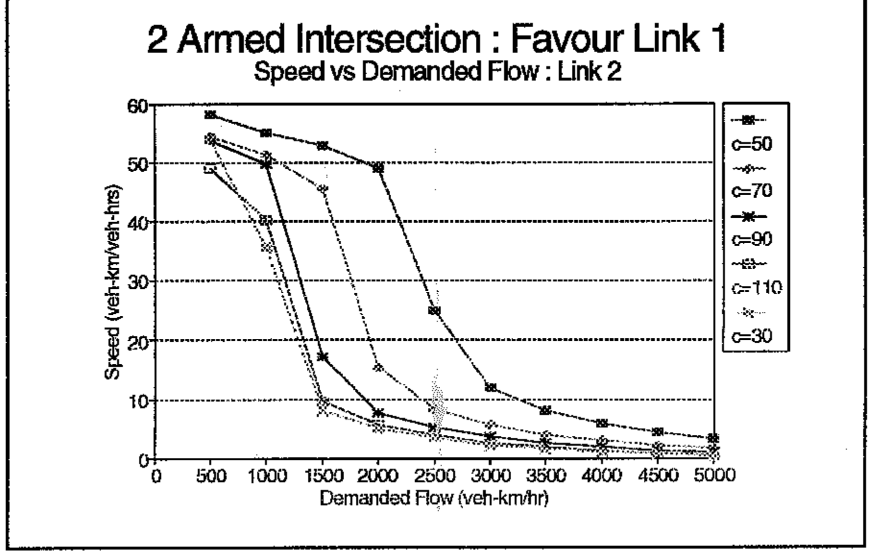
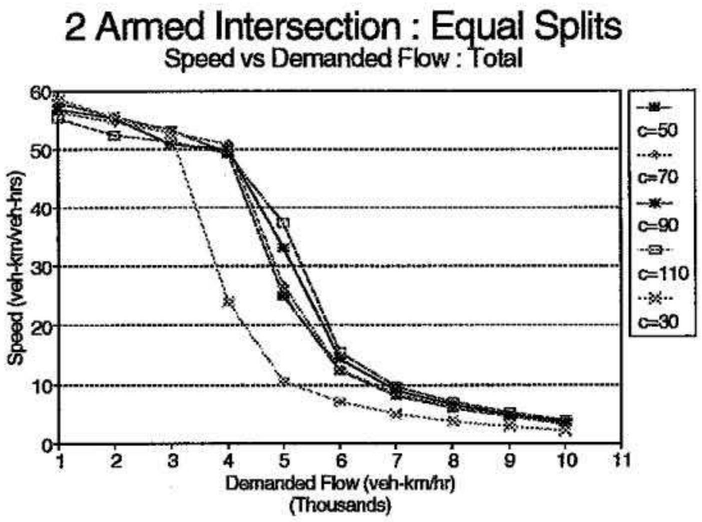


Fig 5



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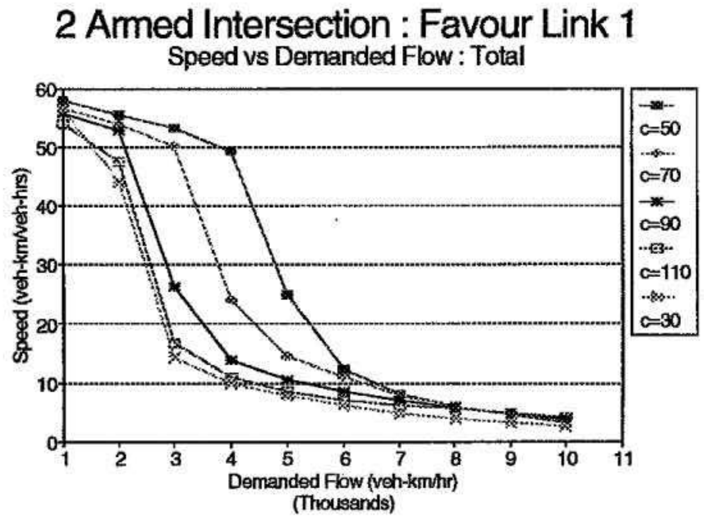


Fig 7

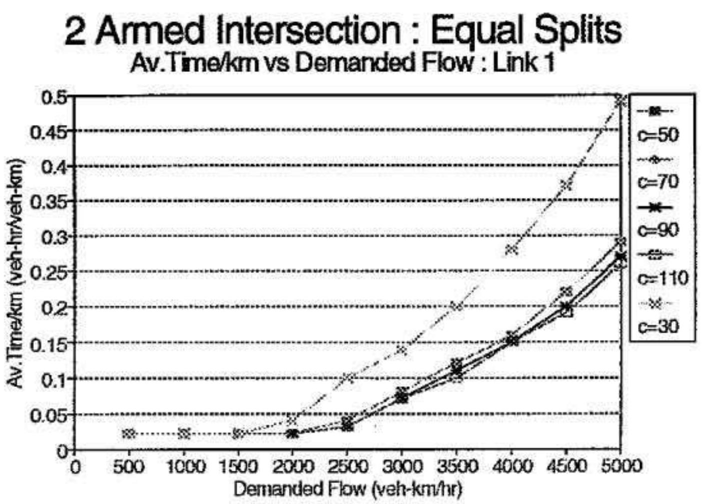


Fig 8

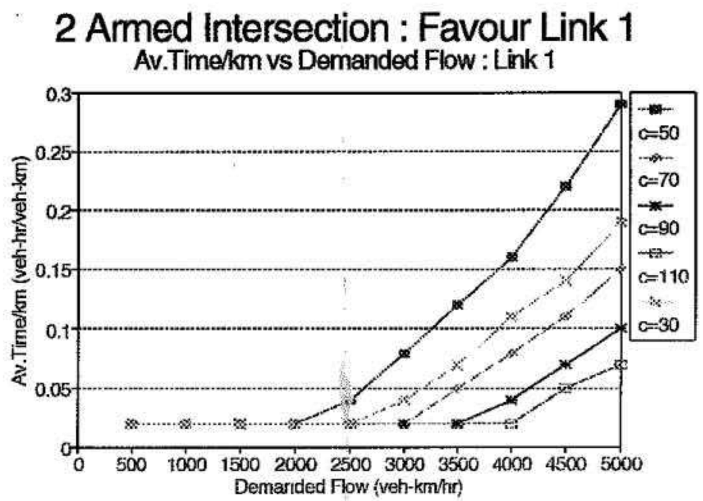


Fig 9

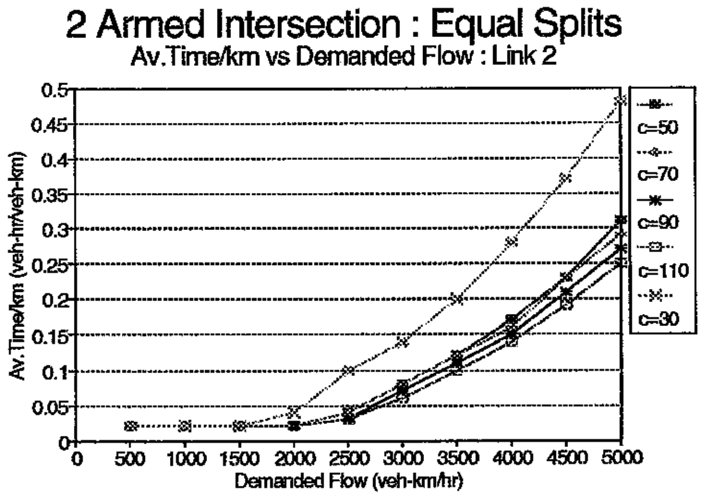
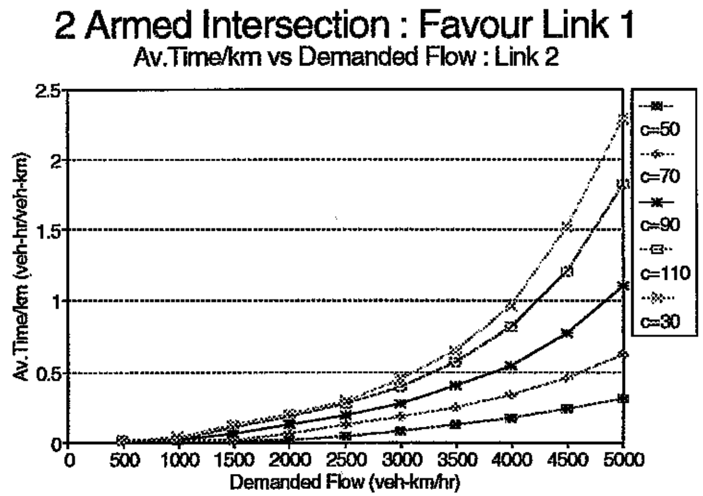


Fig 10



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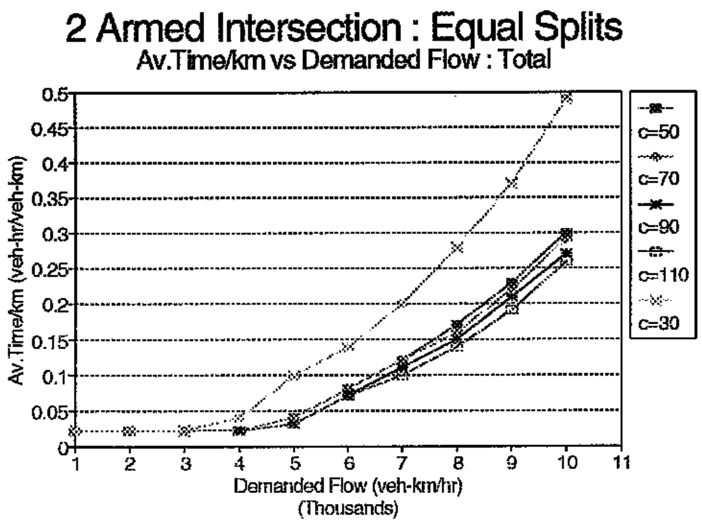

Fig 12

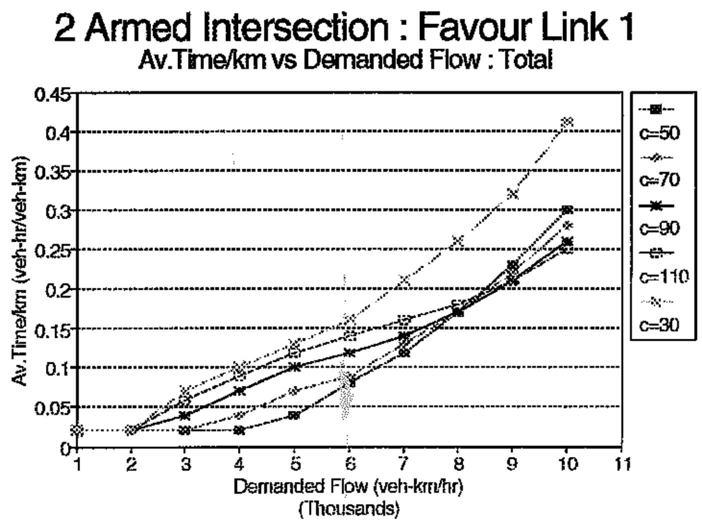

Fig 13

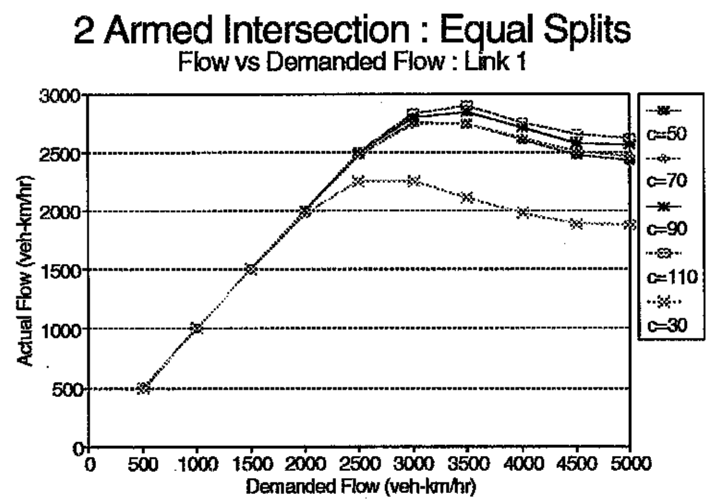

Fig 14

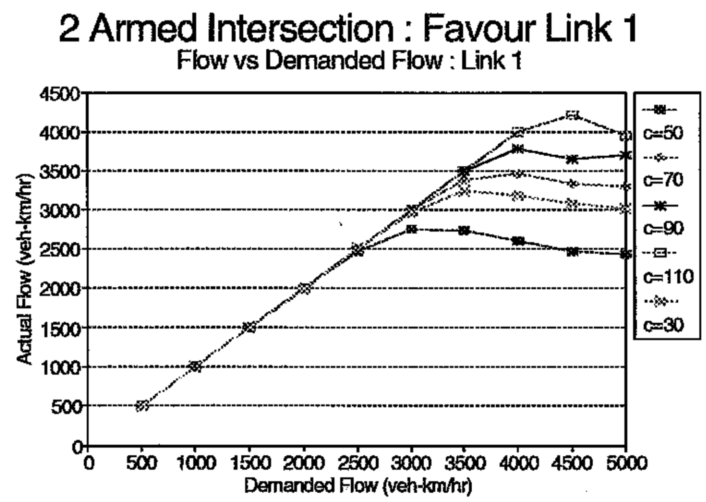

Fig 15

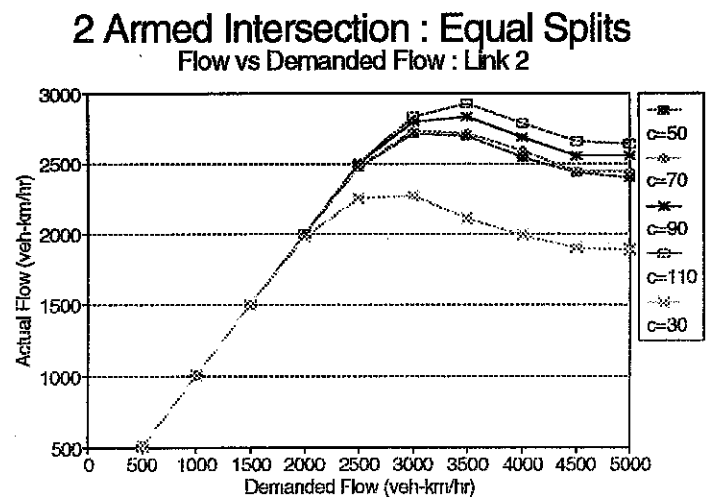

Fig 16

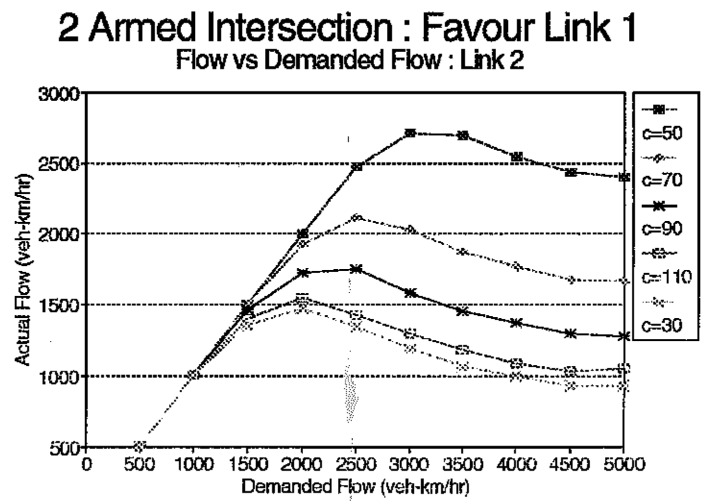

Fig 17

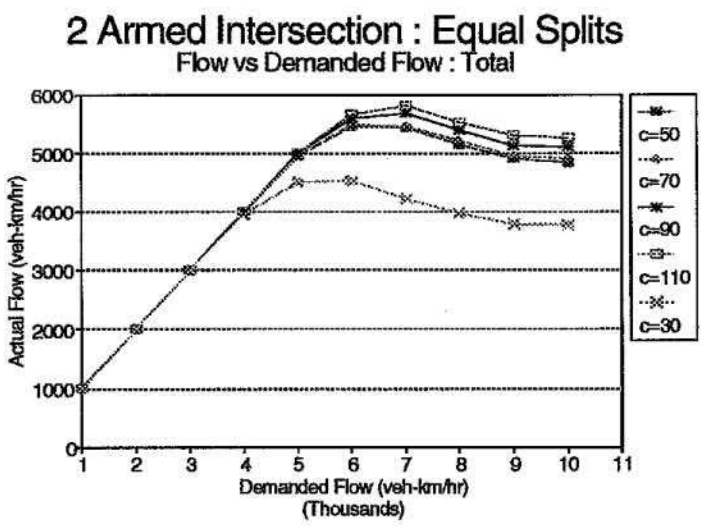
2 Armed Intersection : Equal Splits
Flow vs Demanded Flow : Total
Actual Flow (veh-km/hr)
Demanded Flow (veh-km/hr)
(Thousands)
c=50
c=70
c=90
c=110
c=30

Fig 18

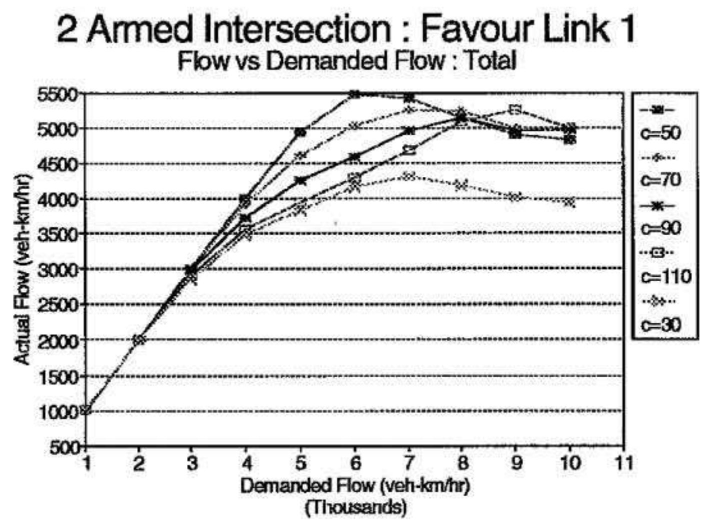
2 Armed Intersection : Favour Link 1
Flow vs Demanded Flow : Total
Actual Flow (veh-km/hr)
Demanded Flow (veh-km/hr)
(Thousands)
c=50
c=70
c=90
c=110
c=30

Fig 19

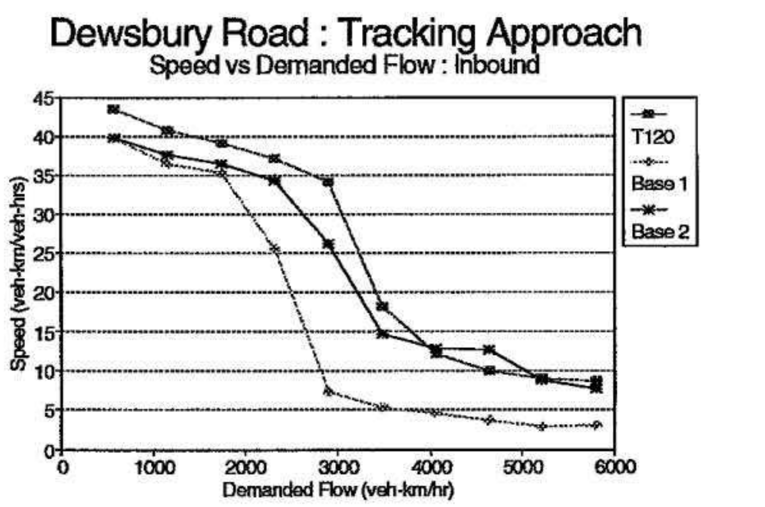

Fig 20

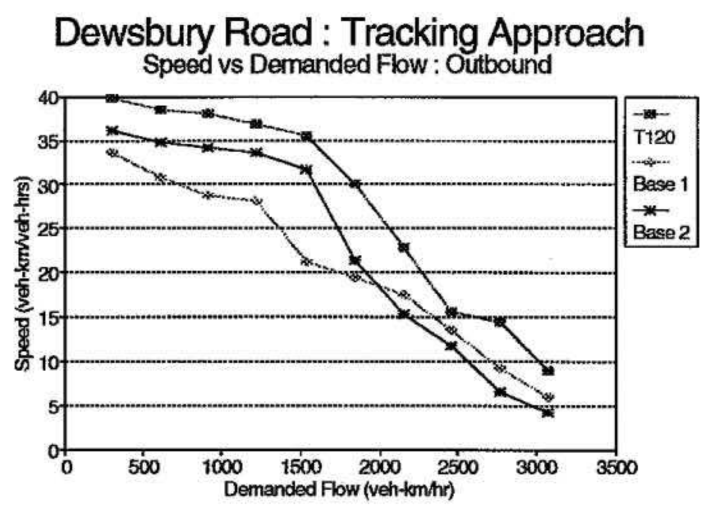

Fig 21

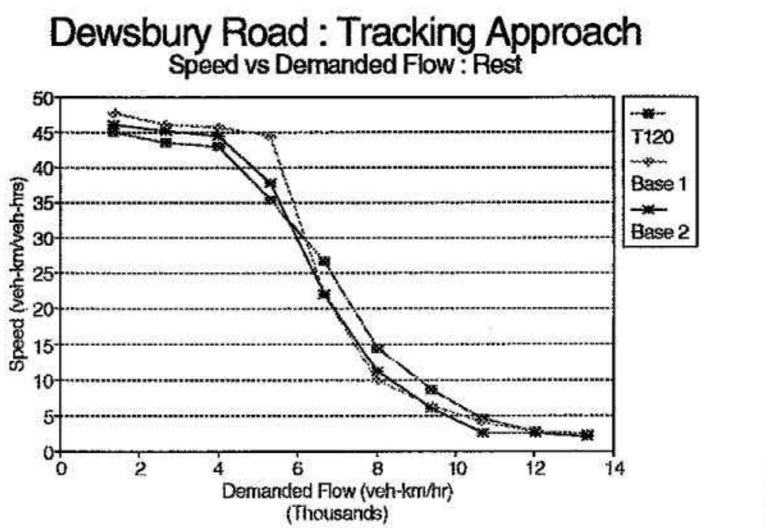

Fig 22

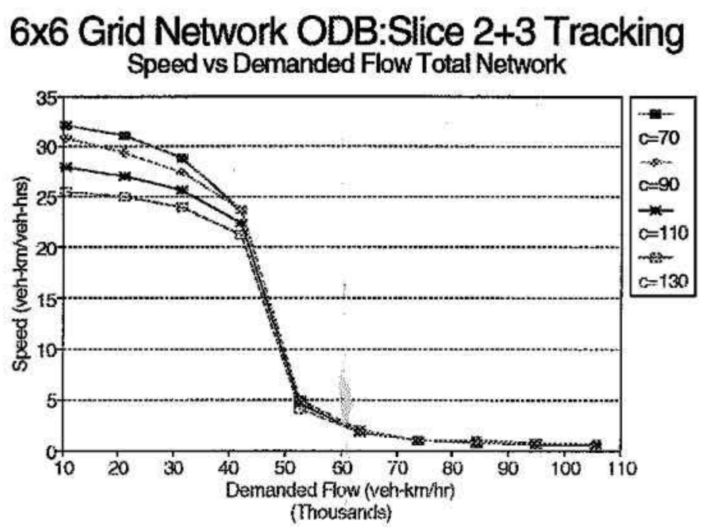

Fig 23

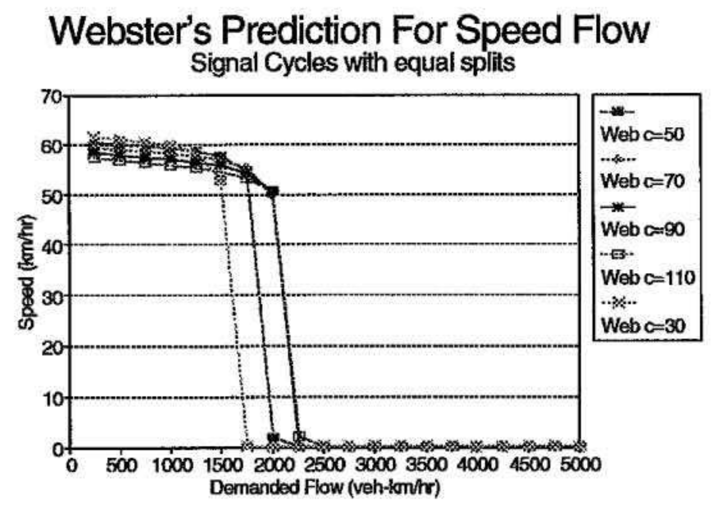

Fig 24

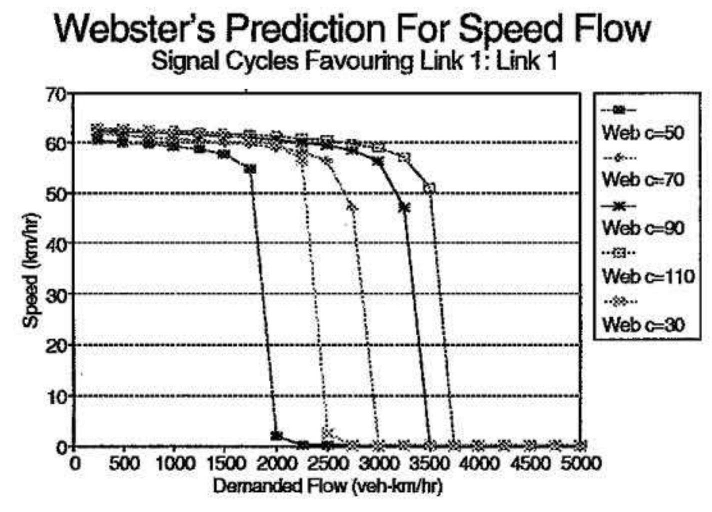

Fig 25

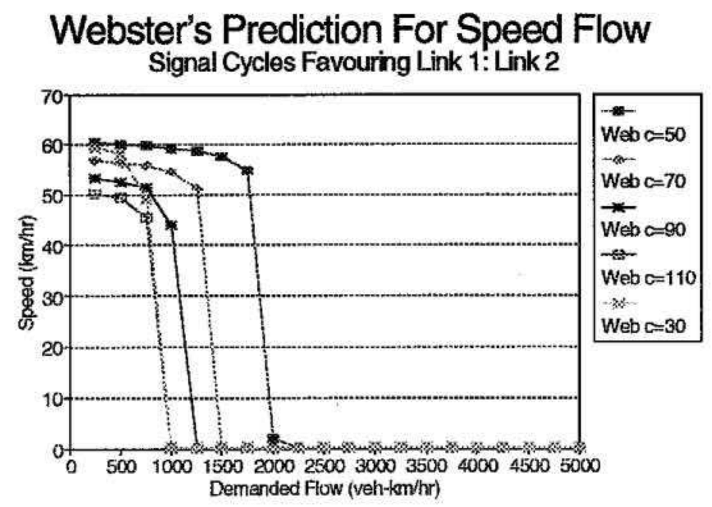

Fig 26